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Reverse running pumps analytical, experimental and computational study: A review

Himanshu Nautiyal *, Varun, Anoop Kumar

Department of Mechanical Engineering, National Institute of Technology, Hamirpur, India

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ABSTRACT

A pump can be used as turbine and has good application in micro-hydropower schemes. Pump as turbine (PAT) is one of the best alternatives for fulfilling the energy demands and providing the electricity in remote and rural areas. In this study a review on the work done in the area of pump working as turbine has been explained. Based upon the literature survey, analytical, experimental and computational works on pump as turbine have been discussed. Several methods for predicting the behaviour of pumps in turbine mode have been developed but no method is appropriate for the entire range of specific speeds. Computational fluid dynamics (CFD) is also used to study the reverse operation of centrifugal pumps, but still results are not yet acceptable.

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1. Introduction

Energy plays an important role in almost all areas of human and commercial activities, and it is very important input for those countries that are developing from economic point of view. Adequate generation of electricity is essential to develop the economy's infrastructure of a country. Electricity generation through the non-renewable sources is quite common. A large number of thermal power plants are running throughout the world for electricity generation but the fast depleting nature and increasing prices of petroleum products (coal, oil, gas, etc.) are the major complications in fulfilling the power demands from these sources. In addition to this, the non-renewable energy sources are not expedient from ecological point of view. They are responsible for producing various gases especially 'CO_2' which is a major greenhouse gas (GHG) and promotes global warming. Other problems like acid rain, toxic wastes are also associated with the use of non-renewable energy sources. These impediments forces to look for other clean and cheap sources for energy generation.

Among all the renewable energy sources, hydropower is the most promising and often used to produce electricity. Table 1 [1,2] shows the growth of electricity generation through thermal, hydro, nuclear since 1950. The figures of the table show that the hydropower generation is increased substantially in the last 50 years.

The hydroelectric power plants are built on small scale as well as large scale basis. Although in latter of 19th century many small hydroelectric plants were in use, the trend in 20th century had been changed to large scale hydro plants [3]. But the importance of

* Corresponding author.
E-mail address: h2nautiyal@gmail.com (H. Nautiyal).

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Nomenclature

H	head (m)
Q	discharge (m^3/s)
D	impeller's minimal diameter (m)
N	rotational speed (rpm)
N_s	specific speed
h	head ratio
q	volumetric flow rate ratio
P	power
kWh	kilowatt hour
PAT	pump as turbine
CFD	computational fluid dynamics
BEP	best efficiency point
IGC	induction generator and controller
SEIG	self-excited induction generator
RO	reverse osmosis
PRV	pressure reducing valve

Greek symbols

η	hydraulic efficiency
γ	specific weight

Subscripts

t	turbine
p	pump
n	net
v	volute losses
l	leakage loss
e	kinetic energy losses
i	losses in impeller

small and micro-hydropower plants have been arisen due to their environment friendly nature and having no problems of large water storage and rehabilitation of population. Also, electricity generation through small hydro is very well for sustainable development [4].

Small and micro-hydro plants are also essential for rural electrification. The electricity problem in rural areas is quite common. In 2001 census, 72% of India's total population was classified as rural and 58% of workers were engaged to agriculture [5]. In rural areas electricity is required for lighting and mechanization of agricultural tasks. The enhancement of rural people totally depends on the productivity in agriculture. Productivity has always been the measure of a successful agriculture operation [6]. Advent of electricity in rural areas is an effective solution of improvement of rural people. Lack of access to energy in remote areas is a major challenge in rural electrification. The area without energy accessibility comprises islands, hills, forest etc. In these areas energy sources are inadequate and conventional power plants are very difficult to establish. Also, delivered cost of electricity produced by coal thermal power plants in remote areas located in the distance range of 5–25 km is found to vary from Rs. 3.18/kWh to Rs. 231.14/kWh depending on peak electrical load and load factor [7].

Small and micro-hydropower projects are the excellent alternative for electricity generation in remote areas. Small scale hydropower projects can be installed on small streams, small rivers, and canals without any recognizable effect on environment. As compared to large scale hydro projects, small scale hydro projects can be installed in less time and with low initial cost without any extensive environmental problem. The Ministry of New Renewable Energy Sources (MNRE), (Govt. of India) has searched about 6000 streams in northern and north eastern India. These streams are not appropriate for establishment of a large scale power plant but can be utilized for electricity generation in between the 5 kW and 100 kW [8]. Small and micro-hydropower projects are the appropriate options for generating electricity by using such water streams. The running cost of such plants is low but initial capital cost is relatively high. So, by reducing the equipment cost in small hydropower projects can become more useful and accessible.

One of the easiest ways to reduce the equipment cost is the use of centrifugal pump in reverse mode and can be used as an alternative to conventional hydraulic turbine. The direction and rotation of flow in a turbine mode of a pump is shown in Fig. 1 [9]. The research on using pump as turbine (PAT) was started around 1930 [10]. In 1961 Kittredge presented the experimental results for four pumps in turbine and pump mode normalized to their best efficiency point (BEP) and related turbine mode performance of a pump to its specific speed [11]. Pumps are mass produced and less complicated to operate than turbine. Pumps working as turbine are an unconventional solution for producing energy in water systems like natural falls, irrigation systems, sewage systems, etc. [12]. KSB Aktiengesellschaft recorded an immense success of PAT in the applications like small hydropower system, major water transport systems, reverse osmosis and industrial systems [13]. In the present study an attempt has been carried out various researches on PAT.

2. Analytical investigation on PAT

Orchard and Klos [13] provided information about the applications and advantages of pump working as turbine. The applications of PAT for water industry were discussed in detail. Fig. 2 shows that the direction of flow in a pump is reversed in turbine mode. In this report, it was shown that the use of reverse running pump is a cost effective way for power production as

Table 1
Growth of energy generation in India [1,2].

S. no.	Year	Thermal (MW)	Hydro (MW)	Nuclear (MW)	Total (MW)
1.	1950	1153	559	–	1712
2.	1960	2736	1417	–	4653
3.	1970	7906	6383	420	14,709
4.	1980	17,562	11,791	860	30,213
5.	1990	43,764	18,307	1565	63,638
6.	2001	73,273	25,574	2860	101,708
7.	2002	76,057	26,269	2720	105,046
8.	2004	80,457	29,507	2720	112,864
9.	2006	89,962	33,193	3900	127,056
10.	2007	90,173	33,600	3900	127,673
11.	2009[a]	96,045	36,917	4120	137,082

[a] Till 30 June 2009.

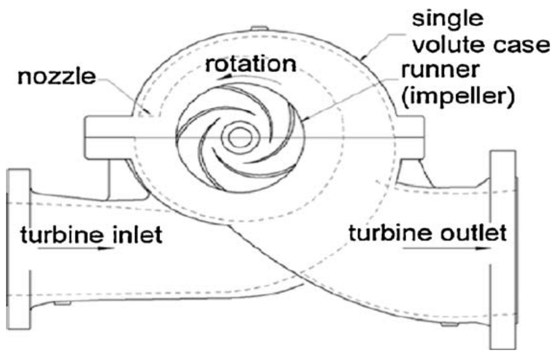

Fig. 1. Direction of flow and rotation in a PAT.

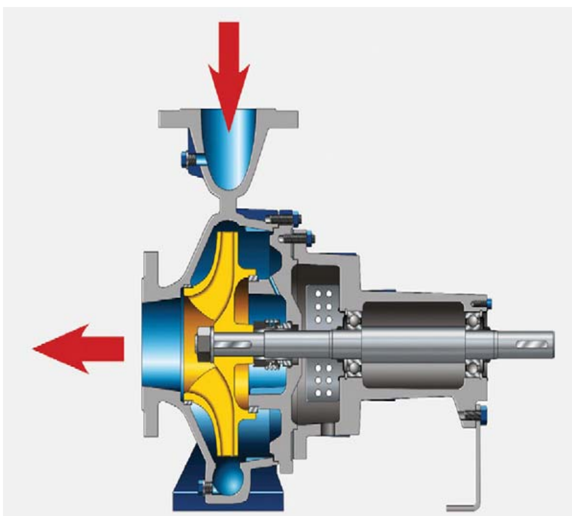

Fig. 2. Sectional view of Etanorm pumps as turbine.

compared to the high efficiency conventional turbines. The application range for ring section and volute casing pumps working as turbine was also discussed.

Williams [14] described a general view of standard pump working as turbine for micro-hydropower plants with three examples of different types of PAT schemes. In this paper, use of induction generator and controller (IGC) design enables the PAT units to be used for isolated micro-hydropower projects. With the help of IGC, appliances can be switched on and off while maintaining a constant voltage output. Few years back, synchronous generators have been used in small isolated hydropower schemes. But, PAT can be used with an induction generator instead of a conventional turbine and provide an option to avoid a belt drive. Many advantages of using PAT with induction generator like easier installation, very low friction loss in drive (saving up to 5% of output power), lower cost, longer bearing life etc were illustrated in this study. Induction motors can be used as generator [15], particularly for sizes up to 30 kW and cheaper than synchronous generators. Single-phase induction motors are also applicable to be used as stand alone generators but problems are arisen in achieving excitation and in predicting the size and arrangement of the capacitors required. However, a good method of providing a single-phase supply was suggested by the use of three-phase induction motor as a single-phase generator [16]. The biggest advantage of PAT is for medium head sites, where practical and cost advantages are in favour of pump instead of use of the other types of turbines. Also, PAT can be used over the range normally covered by multi-jet Pelton turbines, crossflow turbines and small Francis turbines.

Stepanoff [17] stated some relationship for same speed in pump and turbine mode. These relations show that the flow rate ratio and the head ratio in turbine and pump operation are in inverse proportion to the pump efficiency and square of the pump efficiency, respectively, as

$$H_t = \frac{H_p}{\eta_t \eta_p} = \frac{H_p}{\eta^2} \tag{1}$$

$$Q_t = \frac{Q_p}{\eta} \tag{2}$$

$$N_{st} = N_{sp}\eta \tag{3}$$

Various modes of pump operation in the form of four quadrant performance curves were described. The complete performance characteristics for four pumps having specific speeds 1800 (radial), 7500 (mixed), 7500 (axial), and 13,500 (axial) was provided for different operating zones viz. pump normal, pump reverse, turbine normal, turbine reverse.

Gantar [18] studied the propeller pump working in the turbine mode of operation. In reverse running of a propeller pump, the main problematic element is the suction bell-mouth. So, at the impeller discharge in turbine mode the kinetic energy can be utilized by replacing the bell-mouth with carefully designed concentric diffuser or with a diffuser combined with a bend. Diffusor is important in high specific speed pumps because at impeller discharge the part of kinetic energy in total energy is large.

Derakhshan et al. [19] redesigned the shape of the impeller blades to increase the efficiency of the pump in turbine mode by using gradient based optimization algorithm and incomplete sensitivities method [20] for radial turbo-machines. This optimization study has been carried out in two steps: primal optimization and final optimization. The optimization results show that the torque, head and hydraulic efficiency was increased by 4.25%, 1.97%, and 2.2%, respectively. In second optimization, torque, head and hydraulic efficiency was improved by 2.27%, 1.08%, and 1.17%, respectively.

Joshi et al. [21] described a simple stand alone micro-hydro scheme using reverse running centrifugal pump for remote areas as shown in Fig. 3. This system consists of an unregulated PAT directly coupled to SEIG (self-excited induction generator). The SEIG is connected to local loads through inverter-distribution transformer. A method for selection of a pump for working as turbine has been discussed with a case study of a low head micro site producing 25 kW power from the gross head of 5.5 m. In this method the pump characteristics for pumps with different specific speeds by Swanson [22] was used to develop pump operating ratios for PAT in a constant head mode. The selection of the required pump for the project is done by finding out the operating ratios corresponding to the specific speed of that pump. After this, the steady state analysis of the unregulated PAT connected to SEIG was done through computer simulation. Chan's approach [23] was

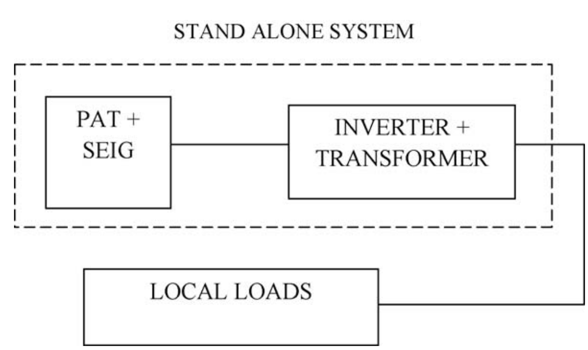

Fig. 3. A general schematic of a stand alone system.

used for simulation of unregulated PAT-SEIG. Variation in different quantities with variation of the load was simulated and results were discussed in detail.

Derakhshan and Nourbakhsh [24] presented some relationship to predict the best efficiency point of PAT. The "Area method" developed by Williams [25] and Anderson [26] based upon theoretical analysis was used to achieve BEP of an industrial centrifugal pump. The method was based on geometrical and hydraulic characteristics of pump in pumping mode. Power losses in the volute and impeller, power losses due to gland packing and bearing cases, disc friction losses in gaps between rotor and stator, volumetric losses due to leakage from clearances between rotor and stator were detected for calculating the head, discharge and efficiency of PAT at BEP. The entire derivation for finding out the relations for BEP of PAT was described in detail. The values predicted by this method were slightly lower than the experimental data. The final relation for turbine maximum efficiency is expressed as

$$\eta_t = \frac{P_{nt}}{\gamma \cdot Q_t \cdot H_t} = \frac{\gamma \cdot Q_t \cdot H_t - P - P_{lt} - P_{et} - P_{it} - P_{mt}}{\gamma \cdot Q_t \cdot H_t} \tag{4}$$

Isbasoiu et al. [27] studied various aspects of standard pump working as turbine. The study shows that PAT is a good and economical solution for power production in small hydropower schemes. The range of heads and flows over which a PAT can operate was discussed in the study. Performance curves in pump and turbine mode and different system control methods with PAT were also discussed. The procedure for the selection of a pump as turbine for a particular site has been explained.

Singh et al. [28] evaluated the field performance of pump working as turbine for a 10 kW capacity micro-hydro scheme at Kinko, Tanzania. A detailed comparison was done between predicted hydraulic characteristics of the given PAT and those obtained by experimentally. From the comparison of hydraulic characteristics it was found that field characteristics were only slightly deviated from the predicted characteristics. At full load point the comparison was very close. At the full load point, the maximum deviation from the predicted value for the net head and discharge were equal to 2% and 4%, respectively. Electric output power was deviated by 3% from the predicted value.

Derakhshan and Nourbakhsh [28] developed a new method for finding out the BEP of a PAT based on pump's hydraulic specification. Some correlations were also presented for pumps with different impeller diameter and for same specific speeds. The values of h and q are obtained by this method which supports the experimental data. This method was valid for pumps with specific speed less than 60. A comparison between different methods for finding out the BEP of PAT was discussed with the values of h and q but no method resembles the experimental data throughout the whole range of specific speeds. In addition to this, some relations were presented for determining complete characteristic curves of a PAT based on its BEP. The results coincide with the experimental data but the method is only useful for estimating the characteristic curves for PAT. Finally, a procedure was also described for selecting a suitable pump to work as a turbine in a small hydro site which is valid for turbines with specific speed less than 150 (turbine).

Gulich [9] described the performance of centrifugal pump in reverse direction by using mathematical equations. Theoretical and actual characteristics of a reverse running centrifugal pumps as turbines were discussed. A complete description of centrifugal pump design and physical force analysis within different turbine portion was also presented.

Sharma [30] described the application of pump technology to small hydroelectric schemes. The paper advocates the use of PAT in small hydropower generation. The end suction centrifugal pumps are always suitable for PAT and axial flow pumps are suitable for low head hydro schemes. In line and double suction can also be used but in turbine mode they are comparatively less efficient. Self-priming pumps are not suitable for PAT application because they have non-return valve to prevent reverse flow. Also, pumps with fin cooling arrangement of motor are not suitable for power production because they overheat unless install below the water level. Performance and selection of PAT was also discussed in detail. The study shows that, ratio of turbine capacity and head at BEP to pump capacity and head at BEP varies with specific speed in the range of 1.1–2.1. The following equations were presented to convert pump data into turbine performance data.

$$Q_t = 1.1 \times \frac{N_g}{N_m} \times \frac{Q_p}{\eta_p^{0.8}} \tag{5}$$

$$H_t = 1.1 \times \frac{N_g}{N_m} \times \frac{H_p}{\eta_p^{1.2}} \tag{6}$$

$$N_g = 240 \times \frac{f}{p} - N \tag{7}$$

N_g is the generator speed at rated frequency $f = 50$ Hz and p = number of poles.

Ramos and Borga [31] presented analysis of steady and transient regimes based on Suter parameters [32]. The main idea pertaining to this analysis was getting a more economic solution to recover some part of dissipated energy. All operating conditions of a pump were described in detail. The developed analysis concluded that pumps as turbines can show a maximum relative efficiency up to 80%, depending on the type of runner and the use of PAT in water supply systems can be an advantageous solution for recovering power.

Williams [33] presented a study on comparison of eight different PAT prediction methods (Stepanoff [17], Sharma [34], Alatorre-Frenk [35], Schmiedl [36], Grover [37], Hergt [38], Hancock [39], Childs [40]) by using the test results on 35 pumps of various types and sizes. The comparison was based on the analysis of the effects of poor turbine prediction on PAT operation. The analysis showed that no method can give accurate prediction for all the pumps but the method proposed by Sharma [34] falls somehow in acceptable limits.

3. Experimental studies

Joshi et al. [41] described a method for selecting a high specific speed pump for low head hydroelectric power generation with a case study of a micro-hydro site producing 25 kW from 5.5 m of gross head. It was an approximate method based on experimental data of three pumps. After that the relationship between pump and turbine specific speeds was established to aid in selection of a pump for a particular site.

$$\frac{N_{st}}{N_{sp}} = \frac{N \times (\sqrt{P}/H^{5/4})t}{N \times (\sqrt{Q}/H^{3/4})\,p} \tag{8}$$

Now, by using BEP values of pump and the above relation, the relationship between the PAT specific speed and pump specific speed was derived for pump selection purposes for equal rotation speeds.

Derakhshan and Nourbakhsh [29] presented some relations to predict the BEP of PAT by testing four centrifugal pumps with specific speeds from 14 to 56 were selected for performing experiments. Input power, head and flow rate for these pumps were 30 kW, 25 m and 0.15 m^3/s, respectively. Synchronous generator was chosen for the experiment and all pumps were tested at 1500 rpm. The complete experimental test rig was described in Fig. 4. After the experiments, it could be concluded that a centrifugal pump can work as turbine in different heads, flow rates and rotational speeds. At the same rotational speeds, a

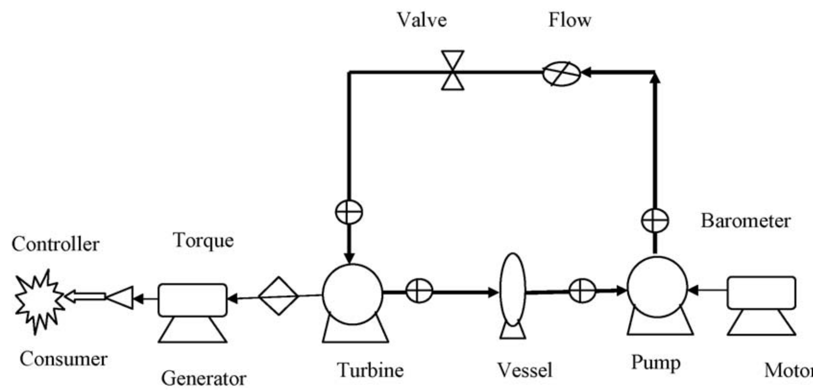

Fig. 4. Mini hydro power setup used by Derakhshan and Nourbakhsh.

centrifugal pump in turbine mode works in higher flow rate and head than in pumping mode. High specific speed pumps have lower head ratio '*h*' and volumetric flow ratio '*q*' but the variation of power ratio did not depend on variation of specific speed of pump.

Gantar [18] tested models of propeller pumps in reverse mode and proposed that, like radial type, the operating point in turbine mode operation of propeller pumps based on pump characteristics is roughly estimated and for the accurate determination of the characteristics in turbine mode of operation the measurements are essentially required. Comparison of the characteristics in pump and turbine mode of a propeller pump of specific speed 180 at five different impeller blades set angles indicated that efficiency is higher in turbine mode and the region of good efficiency in turbine mode was larger than in pump mode due to the adjustment capability of blades of propeller pump to flow changes. This result indicates wide working region in reverse operation of propeller pump and eliminates the greatest drawback of the reverse running operation of standard pumps with fixed geometry, compared with the classical turbines. This analysis also advocated the automatic closing of the impeller blades in case of power breakdown. In the condition of power breakdown the runaway occurs, and then the rotational speed is considerably increased. So, no damage of rotating element is insured at the runaway speed otherwise a flow regulating element is required to reduce the flow automatically when runaway occurs.

Derakhshan and Nourbakhsh [24] carried out an experimental investigation by a laboratory model of mini hydropower plant as shown in Fig. 4. An industrial low speed centrifugal pump with specific speed 23.5 was selected for testing as turbine. The maximum input turbine shaft power, the maximum head and the maximum discharge were 20 kW, 25 m, and 0.12 m^3/s, respectively. Values of PAT head, discharge, output power and efficiency were obtained after the test. A constant odd combination method; based on a 95% confidence level, described by Moffat [42], was used for performing first order uncertainty analysis. The uncertainty of head, rate of flow, power and efficiency were $\pm$5.5%, $\pm$3.4%, $\pm$5.1%, $\pm$5.5%, respectively.

Fernandez et al. [43] carried out investigations with a pump having single axial suction and a spiral casing with an impeller of 200 mm outer diameter with seven backward curved blades of logarithmic profile and concluded that turbine characteristics can be predicted from pump characteristics to some extent. Results were presented with performance curves at constant speed and constant head. The constant speed curves showed that the net head is increased in pump mode and at low flow rates the pump presents an inverse working area with power consumption and head dissipation. An increase of speed with the head was shown in constant head performance curves. Apart from this, the forces actuating on the impeller were studied. Results shows that the forces measured in turbine mode are smaller than the forces measured in pump mode. This shows that increase in material fatigue will not be produced in turbine operation of pump.

4. CFD analysis of PAT

Natanasabapathi et al. [44] used CFX-5.6 software to study the flow through PAT as a test case for which experimental test results were available. BladeGen software was used to create the blade profile. In Pro-Engineer the domain of complete runner was created and transferred to CFX-5.6 Build. In the next step the mesh was generated. The whole geometry was divided into three major domains as Casing, Runner and Draft tube. The result analysis was done with unstructured mesh. The head drop across the turbine was matching with the experimental values but there was a deviation in the efficiency computed from CFD at discharges away from BEP. After this the analysis was done with further refinement of mesh but the error across the frozen rotor interface was not vanished. Then, two rings of structured grid of two element thickness were introduced in between the casing and runner. After this, it was shown that the error was reduced considerably. So, it was concluded that using structured grid near the interface is a solution for eliminating such unrealistic results.

Derakhshan and Nourbakhsh [24] simulated a centrifugal pump with specific speed 23.5 in direct and reverse modes using CFD analysis. A 3D model of the pump was generated which includes the whole impeller and the volute to study the whole circumferential variation of the flow caused by the volute adequately as shown in Fig. 5. To check the numerical results, simulated pump

Fig. 5. 3D model of simulated pump.

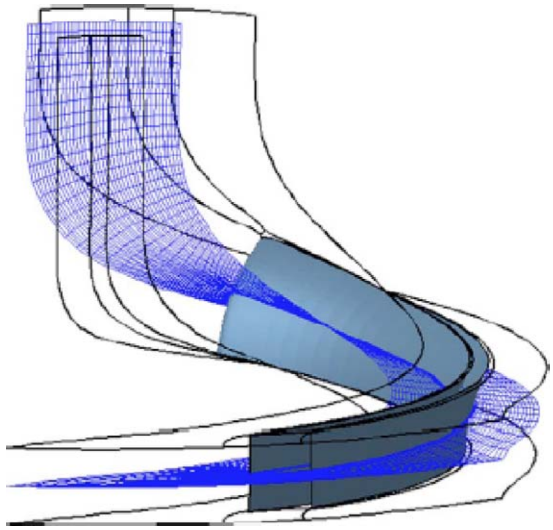

Fig. 6. Computational domain and the grid on midspan.

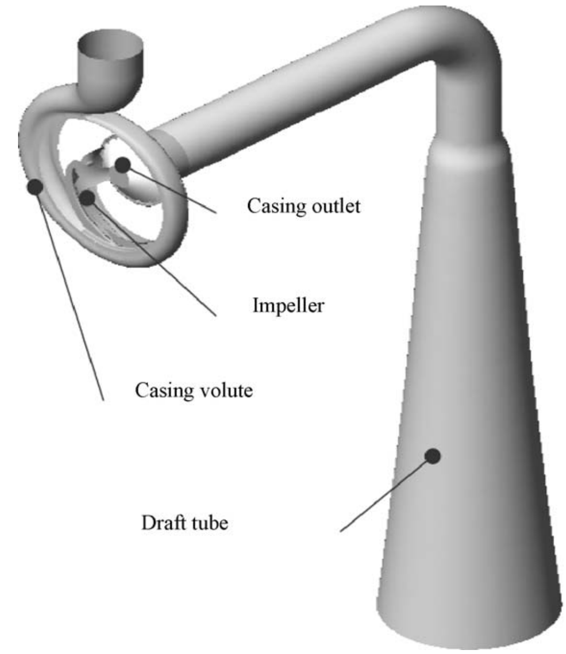

Fig. 7. Flow zones in PAT.

was tested as a turbine in the test rig. CFD results supported the experimental data for pump mode at BEP with part load and overload zones but for turbine mode the results are not matched. At same discharges, CFD values for turbine head and power were lower than experimental data because the flow field in the space between impeller hub/shroud and casing and the sealing gap were not included in the model and the effect of geometrical simplification was likely to be greater in turbine mode. The analysis showed that application of CFD fails in turbine boundary but the future works on CFD application can be improved.

Derakhshan et al. [19] performed 3D flow simulation of the impeller blades redesigned after the optimization process by using FINETURBO V.7 software. AUTOGRID5 mesh generator developed by Numeca [45] was used to prepare multiblock structured grids on the blades. The discrete schemes were second order in space [46] and first order in time with time marching to steady state solutions discrete schemes was used. At the inlet boundary, mass flow rate, velocity direction, turbulence kinetic energy (k), turbulent dissipation (ε) were imposed and at outlet boundary, static pressure was prescribed. A periodic boundary condition was also applied between two blades. The computational domain and the grid on midspan are shown in Fig. 6. The difference of less than 1% for efficiency and head was obtained in the simulation results.

Rawal and Kashirsagar [47] studied the performance of PAT by numerical methods and results were compared with that of the experimental data for the parameters like head number, and efficiency versus the discharge number. The similarity between the numerical and experimental results was found to be satisfactory.

Rodrigues et al. [48] compared numerical results of centrifugal pump with specific speed of 24.5. The comparisons were done at a speed of 800 rpm for all operating conditions of the pump. The CFD predictions of hydraulic parameters match well with experimental results with deviations within 5–10%. The flow regime within the PAT was divided into four major regions as in Fig. 7. The objective of this flow zone analysis was to find out that zone which should be modified to optimize the hydraulic performance of PAT. The analysis of each zone is shown in Table 2.

5. Modification in impeller

Suarda et al. [49] carried out an experimental work on modification of impeller tips of a centrifugal pump as a turbine. Grinding was done on the inlet ends of the impeller tips of a centrifugal volute type pump to produce a bullet-nose shape as shown in Fig. 8 to prevent excessive turbulence for efficiency consideration. After that, testing was done by operating the pump in reverse mode at the maximum head of the pump (13 m) and at various capacities. The results obtained were presented and discussed. After the modification of pump impeller tips, the power and efficiency of PAT was slightly increased. But the modification was recommended for bigger size of volute pumps as turbines only, not for smaller pumps because in smaller pumps the effect of modification on their performance is not significant and they require hard work on modification.

Derakhshan et al. [19] modified optimized impeller by rounding of leading edges and hub/shroud inlet edges in turbine mode as shown in Fig. 9(a) and (b). Then, the impellers were manufactured and tested in a test rig shown in Fig. 4. A centrifugal pump of seven blades of inlet radius in the hub of 0.25 m in reverse rotation with rotational speed 1500 rpm, a flow rate of 126 m^3/h and a total head rise of 38 m is considered for analysis. From the experimental results, it was shown that, efficiency was improved in all flow rates of part load and overload zones. An increase of -2.2%, +9.4%, +14.8% and +2.9% for head, power and efficiency, respectively, recorded by testing the optimized impeller. The experiment shows the higher value for power, head and efficiency. But the head was increased

Table 2
Flow zone analysis in PAT [48].

S. no.	Zone component	Losses (% of total losses)	Remarks
1.	Volute casing	30–40%	Optimization is difficult
2.	Radial clearance	17–20%	Optimization can be contemplated
3.	Rotating impeller	40–45%	Improvement can be done in Impeller inlet zone
4.	Eye and draft tube	60%	Eye region can be modified

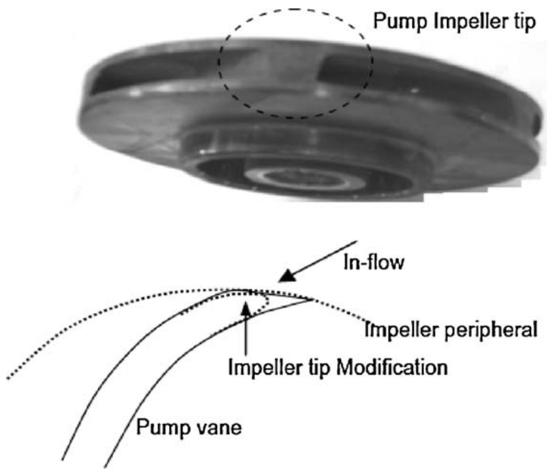

Fig. 8. Modification on pump impeller tip.

slightly more than the numerical optimization data. Rounding of optimized impeller further improved these values to +5.5%, 11.5%, 36.1% and 5.5% for discharge, head, power and efficiency, respectively.

6. Other applications

Apart from electricity production, reverse running centrifugal pumps can be used in other areas. Raja and Piazza [50] described the use of centrifugal pump in reverse operation as hydraulic power recovery turbines for sea water reverse osmosis (RO) systems. In reverse osmosis systems 70% of the energy is wasted at pressures of 800–1000 psi (pounds per square inch). Centrifugal pumps running in reverse direction can be used to recover 80% of that wasted energy. As compared to other hydraulic power recovery turbines, reverse centrifugal pumps do not require complicated and expensive control systems. A simple, most optimum and economical pump motor hydraulic power recovery turbine arrangement in a typical RO system control block was described in Fig. 10. Also, the cost analysis was done on the basis of the plant size, power, cost per kWh and payout periods. The result shows that by using the reverse centrifugal pumps, power consumption per unit volume of the produced water can be reduced considerably and this increases overall plant efficiency. The analysis concluded that PAT are very useful and economical alternative for recovering energy in R.O. systems.

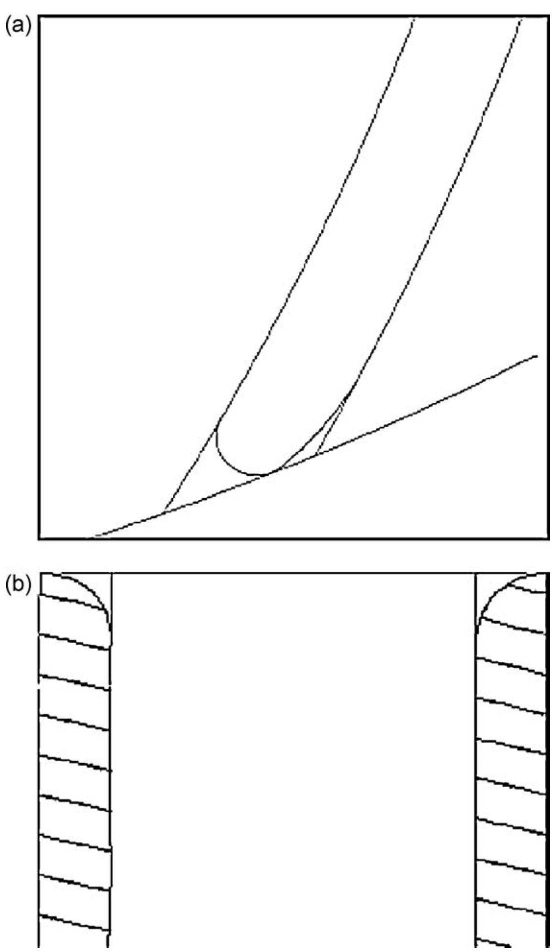

Fig. 9. (a) Rounding of blades profiles at impeller inlet. (b) Rounding of hub shroud inlet edges.

Ramos et al. [51] carried out an experimental investigation to analyse hydraulic system response under steady and transient state conditions and comparison between using a real pressure reducing valve (PRV) and PAT in drinking pipe systems. The aim of this analysis was to show that PAT and micro turbines can be an alternative solution to either control the pressure as well as to produce energy in water distribution systems. A pipe line was connected at upstream to an air vessel, with a volume of 0.8 m^3, and at downstream to an open flow reservoir with a weir which discharges the flow to a constant water level reservoir. The pipe has a length of 200 m, diameter of 0.043 m, thickness of 0.0035 m, roughness of 0.00005 m and a wave speed of 280 m/s. Experimental analysis showed an equivalent response between PRV and PAT for steady state regimes but some expected differences under transient conditions. Also, it was shown that the behaviour of PAT can be better than PRV in some cases but in other cases use of both PAT and PRV was advisable.

Giugni et al. [52] presented a study of recovering energy from water distribution system by coupling and replacing PRVs with PATs. "Napoli Est" (Italy) water distribution networks were taken for case study. EPANET 2.0 [53] was used to carry out hydraulic simulation. Optimization was carried out using PIKAIA Genetic Algorithm [54] supported by NITSOL algorithm [55] as a hydraulic solver. The analysis shows that, reverse running pumps can be replaced or integrated with PATs to minimize losses in water distribution networks. Preliminary economic analysis was also done which shows attractive profits and capital pay-back period for using PATs.

7. Discussions

Pump as turbine is an economical alternative for small and micro-hydro schemes in remote areas. A pump operates more efficiently in turbine mode than in pumping mode. A pump in reverse operation can handled a larger quantity of water than in conventional pumping mode. Higher discharge inside the pump indicates the amount of energy comes out is higher. The main difficulty in using the PAT is finding of turbine characteristics that are required to choose the correct pump for a particular site. The manufacturers do not provide the characteristic curves. So, the knowledge of proper characteristics curves is very essential to understand the operation of centrifugal pump as turbine.

Apart from power production reverse running centrifugal pumps are very useful in reverse osmosis, water distribution system. Efficiency of a PAT is less than a conventional turbine but it is compensated in terms of cost because PAT is cheaper in terms of initial capital cost and maintenance cost. Several researchers have tried to explore the behaviour of PAT but the information relevant to their operation is still very limited. Various PAT prediction

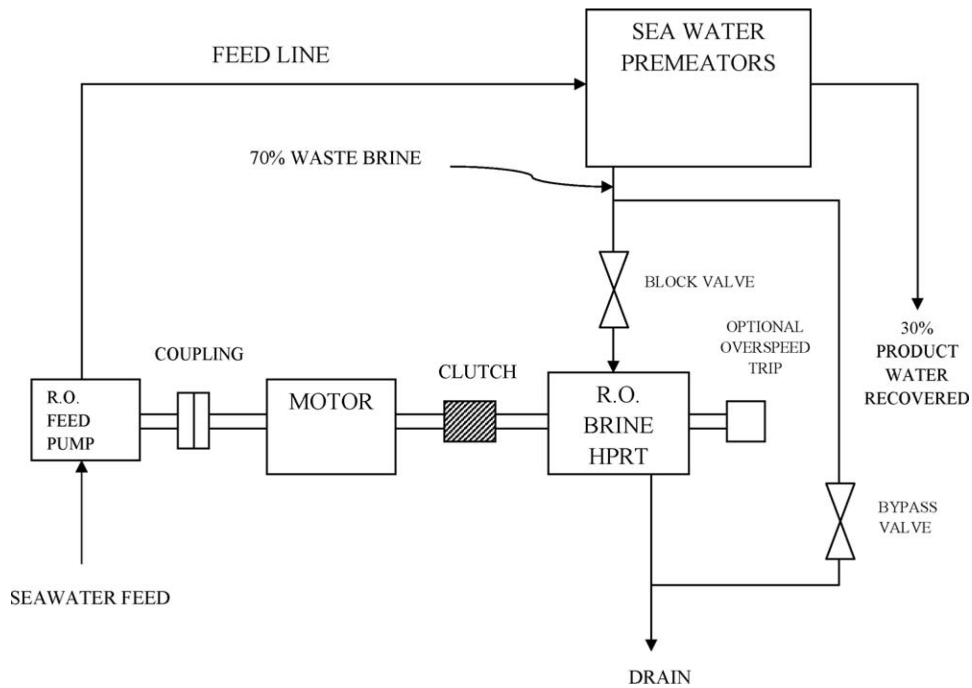

Fig. 10. Arrangement of pump motor hydraulic power recovery turbine in typical RO system control block.

Table 3
Performance prediction methods for pump working as turbine.

S. no.	Name of investigator	Criteria	Head ratio (H_t/H_p)	Discharge ratio (Q_t/Q_p)	Remarks
1.	Stepanoff	BEP	$\frac{1}{\eta_p}$	$\frac{1}{\sqrt{\eta_p}}$	Accurate for N_s in the range of 40–60
2.	Alatorre-Frenk	BEP	$\frac{1}{0.85\eta_p{}^5+0.385}$	$\frac{0.85\eta_p^5+0.385}{2\eta_p^{9.5}+0.205}$	–
3.	Schmiedl	BEP	$-1.4+\frac{2.5}{\eta_{hp}}$	$-1.5+\frac{2.4}{\eta_{hp}^2}$	–
4.	Grover	Specific speed	$2.693-0.0229N_{st}$	$2.379-0.0264N_{st}$	Applied for N_s in the range of 10–50
5.	Sharma	BEP	$\frac{1}{\eta_p^{1.2}}$	$\frac{1}{\eta_p^{0.8}}$	Accurate for N_s in the range of 40–60
6.	Hergt	Specific speed	$1.3-\frac{6}{N_{st}-3}$	$1.3-\frac{1.6}{N_{st}-5}$	–
7.	Childs	BEP	$\frac{1}{\eta_p}$	$\frac{1}{\eta_p}$	–
8.	Hancock	BEP	$\frac{1}{\eta_t}$	$\frac{1}{\eta_t}$	–

methods are presented in Table 3. No PAT performance prediction method closely resembles the experimental data throughout the entire range of specific speeds. Also, any effective study on modification of impeller for PAT is not found.

CFD techniques have also used to study the behaviour the pump in direct and reverse mode. They give useful knowledge of hydraulic losses in the pump. But, the CFD results support the experimental data for pump mode but in turbine mode they are not acceptable. There is a need to use appropriate geometric models for computational study. Future works in the field of CFD can be very useful in exploring the behaviour of pumps in turbine mode.

8. Conclusion

PAT is a good solution for electricity generation in remote and rural areas. They can also be successively used in RO and water distribution systems. Many researchers have been tried to study the reverse working pumps but still there is a need to focus more attention in this area. No prediction method gives accurate results for entire range of specific speed. Although, the studies related to modification in pump impeller are few but it can give quite attractive results. Also, CFD studies are inadequate to explore the PAT areas. Accurate convergence of numerical results with experimental data has not been achieved yet. Future works in the areas of CFD can open new doors to understand PAT.

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